Large-distance effects on spin observables at RHIC*

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Abstract The impact of large-distance contributions on the behaviour of the slopes of the spin-non-flip and of the spin-flip amplitudes is analysed. It is shown that the long tail of the hadron potential in impact parameter space leads to a larger value of the slope for the spin-flip amplitude (without the kinematic factor $\sqrt{|t|}$) than for the spin-non-flip amplitude. This effect is taken into account in the calculation of the analysing power in proton-nucleus reactions at high energies.

The recent data from RHIC and HERA indicate that, even at high energy, the hadronic amplitude has a significant spin-flip contribution, $\mathcal{A}^h_{sf}$, which remains proportional to the spin-non-flip part, $\mathcal{A}^h_{nf}$, as energy is increased. Theoretically, when large-distance contributions are considered, one can obtain a more complicated spin structure for the pomeron coupling. The dependence of the hadron spin-flip amplitude on the momentum transfer at small angles is tightly connected with the basic structure of hadrons at large distances. We show that the slope of the "reduced" hadron spin-flip amplitude (*i.e.* the hadron spin-flip amplitude without the kinematic factor $\sqrt{|t|}$) can be larger than the slope of the hadron spin-non-flip amplitude as was observed long ago [1, 2]. This large slope has a small effect on the differential hadron cross section and on the real part of hadron non-flip amplitude [3].

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The helicity amplitudes can be written

$$\Phi_i(s,t) = \phi_i^h(s,t) + \phi_i^{em}(t)\exp[i\alpha_{em}\varphi_{cn}(s,t)], \; i = 1, ...5$$

where $\phi_i^h(s,t)$ comes purely from strong interactions, $\phi_i^{em}(t)$ from electromagnetic interactions ($\alpha_{em} = 1/137$ is the electromagnetic constant) and $\varphi_{cn}(s,t)$ is the electromagnetic-hadron interference phase factor. The "reduced" spin-flip amplitudes are defined as $\tilde{\mathcal{A}}_{sf}^h(s,t) = \phi_5^h(s,t)/(s\sqrt{|t|})$ and $\tilde{\mathcal{A}}_{sf}^c(s,t) = \phi_5^{em}(s,t)/(s\sqrt{|t|})$. As usual, we define the slope B of the scattering amplitudes as the derivative of the logarithm of the amplitudes with respect to t.

The contribution of large distances was studied in [4, 5]. We present here the results of a a numerical calculation of the relative contributions of small and large distances. We calculate the scattering amplitude in the Born approximation for form factors exponential or Gaussian in impact parameter space, as a function of the upper limit b of the corresponding integral

$$\phi_1^h(t) \;\; \sim \;\; \int_0^b \rho \; d\rho \; J_0(\rho\Delta) f_n, \;\; \phi_5^h(t)/q \sim \int_0^b \rho^2 \; d\rho \; J_1(\rho\Delta) \; f_n. \quad (1)$$

with $f_n = \exp\left[-(\rho/5)^n\right]$, and $n = 1, 2$. We then calculate the ratio of the slopes of these two amplitudes $R_{BB} = B^{sf}/B^{nf}$ as a function of b for these two values of n. The result is shown in Fig.1. We see that at small b the value of R_{BB} is practically the same in both cases. However, at large distances, the behaviour of R_{BB} depends on the form factor: in the Gaussian case, R_{BB} reaches its asymptotic value ($= 1$) quickly, but in the exponential case, it reaches its limit $R_{BB} = 1.7$ only at large distances. These calculations confirm our analytical analysis of the asymptotic behaviour of these integrals at large distances.

We can now use these results in the description of the analysing power at small momentum transfer, for which there are very few high-energy data. We take the hadron spin-non-flip amplitude in a simple exponential form, normalised to the total cross section [7], and with a size and energy dependence of the slope proportional to their values from *pp*-scattering [6].

We assume that the slope slowly rises with $\ln s$ in a way similar to the *pp* case, and normalise it so that the spin-non-flip amplitude has a slope of 62 GeV^{-2} at $p_L = 600$ GeV/c and $|t| = 0.02$ GeV^2. We parametrise the spin-flip part of $p^{12}C$ scattering as

$$\mathcal{A}_{sf}^h(s,t) \;\; = \;\; (k_2 \; + \; i \; k_1)\frac{\sqrt{|t|} \; \sigma_{tot}^{pA}(s)}{4\pi}\exp\left(\frac{B^-}{2}t\right) \quad (2)$$

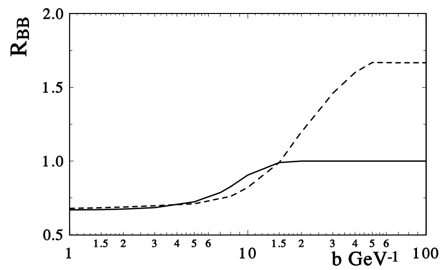

Figure 1: The ratio R_{BB} of the effectively slopes for $n = 1$ (dashed line) and for $n = 2$ (solid line) the upper bound b of the integrals.

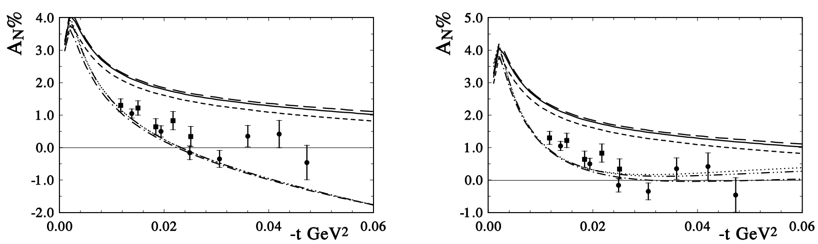

Figure 2: Left: A_N with hadron-spin-flip amplitude in case I ($B^- = B^+$) for $p_L = 24,\ 100,\ 250$ GeV/c. (dash-dot, dashed-dots and dots correspondingly). Right: same as left, but in case II ($B^- = 2B^+$)

According the above analysis, we investigate two extreme cases for the slope of the spin-flip amplitude: I - the spin-flip and the spin-non-flip amplitude have the same slope $B^- = B^+$; II - $B^- = 2B^+$. From the full scattering amplitude, the analysing power is given by

$$A_N \frac{d\sigma}{dt} = -4\pi[Im(\mathcal{A}_{nf})Re(\mathcal{A}_{sf}) - Re(\mathcal{A}_{nf})Im(\mathcal{A}_{sf})], \tag{3}$$

each term having electromagnetic and hadronic contributions.

In Fig. 2, we show A_N calculated for the two possible slopes of the hadron spin-flip amplitude (cases I and II). We see that in both cases we obtain a small energy dependence. In case I, when $B^- = B^+$, A_N decreases less with $|t|$ immediately after the maximum. But at large $|t| \geq 0.01\mathrm{GeV}^2$ the behaviour of A_N is very different: we can obtain a zero for A_N at $|t| \approx 0.02\mathrm{GeV}^2$, after which A_N becomes negative and grows in magnitude. In case II, when $B^- = 2B^+$, A_N approaches zero, may become slightly negative and then grows positive again.

When we come to super-high energies, there may be some additional

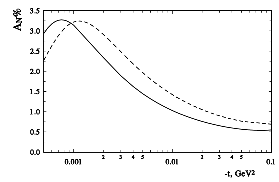

Figure 3: A_N for pp-scattering (without hadron-spin flip amplitude) at $\sqrt{s} = 14$ TeV (hard and dashed lines - with and without saturation)

effects connected with the saturation of the unitarity bound for some values of the impact parameter. This can lead to different values for the analysing power. We calculate such effects in the framework of a model with two simple poles, the second one corresponding to contribution of the hard pomeron. Fig. 4 shows that the effect of the saturation moves the maximum of A_N to smaller values of t. Note that if we observe A_N only in a region of t after the maximum, it will seem smaller, and we may wrongly conclude that such effect comes from the hadron spin-flip amplitude. This situation can also occur in pA-scattering at lower energies.

In conclusion, accurate measurements of the analysing power in the Coulomb-hadron interference region will reveal the structure of the hadron spin-flip amplitude. This in turn will give us further information about the behaviour of the hadron interaction potential at large distances. A definite example of the interplay between long and short distances can be found in the peripheral dynamic model [8, 9], which takes into account the contribution of the hadron interaction at large distances, and in which the calculated hadron spin-flip amplitude leads to a difference in the slopes of the "reduced" spin-flip and spin-non-flip amplitudes at small momentum transfer.

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